bolism very near the time of the last meal, and we cannot, therefore, exclude reactions with a high velocity coefficient which would give a metabolism of measurable amount only in the immediate neighbourhood of zero time.

Moreover, a large number of simultaneous reactions would compound approximately to a logarithmic curve, provided they were separately logarithmic, or very nearly so, and had velocity coefficients not diverging far from the mean. No doubt many vital processes do, in fact, proceed more or less in accordance with the logarithmic law, and it may be that the results obtained by the writers indicate merely that the velocity constants of the chemical changes concerned in the metabolism are not greatly different.

The work that has been done is plainly incomplete. The writers intend to pursue the investigation further—in the first instance in the directions already indicated. Such success as has been achieved in the experiments described above is in no small degree due to the care and skill of Captain J. S. Morgan, M.C., B.A., who has had entire charge of the hog and has kept him in perfect health throughout the work.

Electric Current as a Stimulus, with Respect to its Duration and Strength.

By Seichi Jinnaka and Ryotaro Azuma.

(Communicated by Prof. E. H. Starling, F.R.S. Received May 3, 1922.)

(From the Physiological Laboratory of Tokyo Imperial University, Japan.)

Our experiments on the excitatory effect of an electric current have been carried out by examining the relation between the current-duration and its liminal strength. From the determination of the optimal electric stimuli of amphibian muscle and nerve by the condenser method (1) (2), and from the investigations on the relation of the current-duration to the liminal current-strength (3) (4), Keith Lucas confirmed that there should exist three substances, at least, in a normal sartorius muscle of frogs and toads; each substance being distinguished by its own "excitation time," that is, the substance α represents the muscle material, γ the intramuscular nerve material, and β the intermediary substance; the first showing the longest, the second the intermediate, the third the shortest "excitation time." His further investigations upon the excitatory process (5) (6), led him to confirm the validity of A. V. Hill's excitation formula in all respects (7) (8). The essential part of our present paper consists of the discussion upon these works.

PART I.—EXPERIMENTS ON A MUSCLE AS A WHOLE.

Apparatus and Method of Experiment.

On the whole, we adopted Lucas' method (3) with some modifications in detail.

(1) *Rotating Contact Breaker* (*Spring-rheotome*).—The results of Lucas' experiments were obtained with currents not exceeding 0·02 second in duration (4). But he indicated the possibility of analysing two different muscle substances, as suggested by Grützner, by using currents of longer duration. For this purpose we used a new rotating contact breaker, devised by Prof. Hashida in our laboratory, by which the duration of stimulating currents could be changed accurately within a fairly wide range, say, from 0·0001 to 0·27 seconds. The important parts of the apparatus are shown in fig. 1.

A_1 and A_2 are two horizontal brass arms attached to the rotating axis B, and a short vertical branch of A_1 is caught by a clasp C, while that of A_2 presses the spring S. By pressing down the lever arm of the trigger T, the arms A_1 and A_2 are shot in motion by the spring, knocking down two contacts, at first K_1 by A_1, and then K_2 by A_2. While K_1 is fixed on the brass disc D,

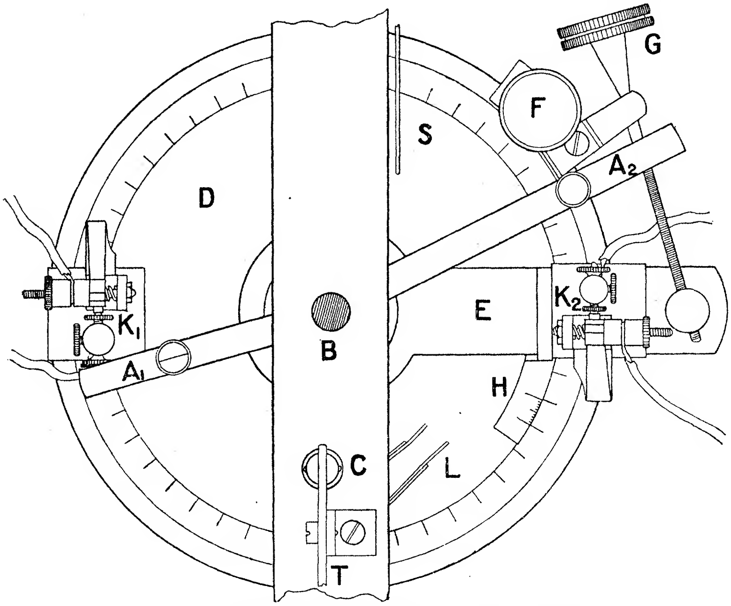

FIG. 1.—Diagram of rotating contact-breaker.

the position of K_2 is changeable, being attached to a movable plate E, which is fixed to any position by the screw F, and fine adjustment can be obtained by the fine screw G.

On a small brass piece H, attached to E, one division of the scale on the circular disc is divided into ten, and the fine adjustment above-mentioned is carried out by means of this fine scale. K_1 and K_2 are surface contacts between platinum plates which are carefully flattened and polished to fit well, for the perfect contacts are essential to the gradation of current-strength. L is the buffer to catch the vertical branch of A_1 after the rotation.

For the purpose of lessening the velocity of rotation, lead weights are placed symmetrically on both ends of the upper horizontal arm attached to the axis (not shown in the figure), and we used three different speeds for the present experiments.

(2) *Stimulating Circuit and Resistances.*—To obtain a constant current of definite strength and duration we adopted the arrangement which was suggested by Lucas. The principle is shown in the following sketch (fig. 2).

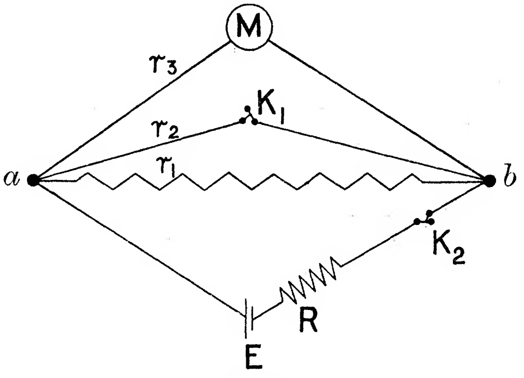

Fig. 2.

If the two contacts K_1 and K_2 are both closed, the current through the circuit aMb may be very small, as the resistance of muscle M is obviously far greater than that of K_1. But, for the accuracy of the experiment, this small residual current is not to be neglected, and ought to be reduced practically to zero.

Generally speaking, the current through the p-th branch of a complex circuit system which involves n branches, is expressed as follows :—

$$i_p = \frac{E}{r_p} \frac{1}{R\Sigma 1/r_n + 1}$$

where r_p represents the resistance of the p-th branch, R the resistance of the main circuit, E the electro-motive force applied.

In the present case, there are three branches, the resistances of which are r_1, r_2, and r_3, and the residual current is to be expressed as

$$i_3' = \frac{E}{r_3} \frac{1}{R(1/r_1+1/r_2+1/r_3)+1}.$$

When the contact K_1 is opened, a stimulating current of the following strength will be obtained, until the break of K_2:—

$$i_3 = \frac{E}{r_3} \frac{1}{R(1/r_1+1/r_3)+1}.$$

Assuming R and r_3 very large and r_2 very small, the ratio of the residual and stimulating current will be simplified as follows:—

$$\frac{i_3'}{i_3} = \frac{r_2}{r_1}.$$

Since $r_2 = 0{\cdot}001$ ohm in our case, it is possible to reduce

$$\frac{i_3'}{i_3} \text{ to } \frac{1}{100{,}000}$$

by using 100 ohms resistance for r_1, and we never use r_1 less than 100 ohms. Thus the residual current is practically zero so far as our experiments are concerned.

If $E = 10$ volts, $R = 20{,}000$ ohms, $r_3 = 10{,}000$ ohms and $r_1 = 100$ ohms, then the stimulating current is

$$i_3 = \frac{Er_1}{Rr_1+Rr_3+r_1r_3} = 4{\cdot}92 \times 10^{-6} \text{ amp.}$$

The increase of i_3 resulting from the increase of r_1 by 1 ohm is 5×10^{-8} amp. In the case where $r_1 = 1000$ ohms, the increase is $3{\cdot}8 \times 10^{-8}$ amp. So that, with this arrangement, the stimulating current can be modified fairly continuously by using an ordinary resistance box.

(3) *Calibration of Current-duration.*—In place of the muscle in the stimulating circuit, we inserted Einthoven's string-galvanometer, the string being stretched to the margin of aperiodic vibration. The movement of the string, which was projected on a rapidly rotating photo-film, shows the moment of "make and break" distinctly. At the same time, a tuning-fork, the number of vibrations adjusted to 100 per second, was set in motion as the time-recorder. Thus we obtained three sets of records according to various positions of K_2 in reference to K_1 and various velocities of rotation. On these records we measured the interval between the points of "make and break" accurately to 0·1 mm., and calculated the current-duration in comparison with the tuning-fork vibration. The results showed that the velocity of rotation was quite uniform within the range of our experiments,

at three different speeds. Then the observation equation must be $y = a + bx$, where y is current-duration, x the reading of scale, and a, b constants. By the Gauss method of solving a set of linear equations, we obtained the following equations for three speeds of rotation. For the first speed :—

$$y = 0{\cdot}00029 + 0{\cdot}000191x;\ \text{probable error} = \pm 0{\cdot}46 \times 10^{-4}.$$

For the second speed :

$$y = 0{\cdot}00047x;\ \text{probable error} = \pm 0{\cdot}48 \times 10^{-3}.$$

For the third speed :

$$y = 0{\cdot}00069x;\ \text{probable error} = \pm 0{\cdot}4 \times 10^{-2}.$$

The maximum value of x available being 390 for our apparatus, we could change the current-duration from 0·0001 to 0·27 seconds.

(4) *Electrode and Material of Experiments.*—We adopted the non-polarisable fluid-electrode, slightly modified from Lucas' (1) and Mines' (12) originals; that is, in place of porcelain filter tubes we inserted layers of 10 per cent. gelatine-Ringer gel, of about 5 cm. thickness, between saturated Zn-sulphate and Ringer's solution. To prevent the contraction of gelatine layers and the diffusion of Zn-sulphate through them, the electrode was thoroughly washed out and kept in Ringer's solution after the experiments. After every two days' experiments we renewed the gelatine layers.

The muscle was suspended in the fluid by means of a glass hook or attached to a light lever or a small mirror (optical lever), and the minimal twitch of the muscle or the slightest movement of the lever was observed.

As the material for experiments, we used almost exclusively M. sartorius and cutaneus dorsi of frogs (*Rana esculenta*), except in few cases sartorius muscle of toads (*Bufo vulgaris japonicus*).

In the preparation of M. cutaneus dorsi, we followed the description of Lucas (9, 10), but we always dissected the muscle with a small piece of bone attached to the pelvic end and a piece of skin on the other end. After the excision of the muscles, they were immersed in Ringer's solution for 3–6 hours before the commencement of experiments, as Lucas (11) stated that it took a couple of hours before excised muscles recovered from mechanical disturbances of dissection and attained an equilibrium state. By such precaution we could avoid the change of excitability during the experiment.

The electrical resistance of the electrode, including the muscle, was determined after each experiment. If an air space was inserted in the electrode as a closed moist chamber, as in Lucas' method, the resistance was about 10,000 ohms. But in the case of Mines' methods it was 4000–6000 ohms.

Results.

As shown in the following Tables and figures (Examples 1, 2, 3 and 4) it is obvious that the current-strength and current-duration curves, obtained from the experiments made on the middle region of muscles, are all discontinuous. However, the number of breaks in each curve is far greater than we should expect from the experiments of Lucas. In Example 2, we notice the abrupt changes of the character of twitch; and some of them coincide with the break of continuity in the curve. This was observed by Lucas (3) in his experiments with lobsters, in which he confirmed that each break in the continuity of a duration-voltage curve implies a change in the excitable substance immediately affected by the stimulus. If we accept his confirmation, we might conclude that there were several substances of different excitability in M. sartorius and even in M. cutaneus dorsi; the latter consists of only 150–200 fibres. Moreover, most of these different excitable substances are to be attributed to the muscle element, as shown by the action of curare (Example 5).

According to Lucas' experiments (4), the muscle substance α is less affected by strong doses of curare than is β-substance, while γ-substance is no longer in functional connection with the muscle after weak doses of curare have been given. In our example, there are also no curves corresponding to β- and γ-substances, but there are at least three breaks in the curve, each accompanying a change in the character of twitch. So far, Lucas' and our experiments have shown no grave discrepancy. But, in the next experiment on the pelvic end of sartorius muscle (Example 6), we found, by applying moderately strong current, a curve which is quite similar to that of so-called β-substance; the consequence of which is quite inexplicable by his theory. Besides this, it seems also to be an unlikely explanation that there exist several muscle-fibre groups of different excitability in the muscle, especially in so small a muscle as M. cutaneus dorsi.

Before proceeding to further experiments, we have to consider various conditions involved in the electrical stimulation of muscles, especially the stimulating current. Lucas seems to have deduced his conclusion on the possibility of the analysis of complex excitable tissues by their response to electric currents of short duration, from the premises that the stimulating constant current is to be conducted to all excitable tissue elements involved in the excitation, without changing the current form. Otherwise, it is impossible to analyse the complex excitable tissues from their response to electric currents without dealing with the nature of currents in every part of the tissues, for, besides the final strength and duration, the form of currents is to be taken into account in the stimulating action of electric currents of short duration.

On the other hand, if we assume that stimulating currents might be deformed in the tissue, it is conceivable that even the muscle consisting of fibres of uniform excitability may appear to some extent as a complex excitable tissue in regard to its response to short-duration currents. From this point of view, the apparently complex curve obtained from the strongly curarised muscle and the presence of β-like substance in the nerve-free region of muscle seem to us to reveal the importance of the unknown problem about the deformation of the stimulating current in the excitable tissues.

Thus, to avoid the confusion of the real difference of excitatory process in different excitable tissues, and the different effects of the stimulating currents due to the current deformation, our further experiments were carried out on a single muscle-fibre by means of the capillary electrode and microscopic observation.

Example 1 (Table I).—Middle Part of Frog's Sartorius; 4½ hours after excision. Bathing fluid: Ringer's solution. Temperature 15·9° C.

Table I.

Current-duration in seconds (t).	Liminal voltage in volts (e).	Current-duration in seconds (t).	Liminal voltage in volts (e).
Inf.	0·107	0·02989	0·281*
0·1833	0·144	0·02894	0·299
0·1739	0·144	0·01939	0·299
0·1457	0·144	0·01748	0·299
0·1269	0·144	0·01557	0·303
0·1175	0·144	0·01366	0·309
0·1081	0·144	0·01175	0·322
0·0940	0·156	0·00984	0·333*
0·0893	0·157	0·00793	0·343
0·0846	0·158	0·00602	0·363
0·0799	0·160	0·00411	0·396
0·0705	0·176	0·00221	0·488
0·0611	0·209*	0·00200	0·509
0·0423	0·248	0·00181	0·528
0·03849	0·250	0·00162	0·563*
0·03658	0·252	0·00143	0·581
0·03467	0·256	0·00124	0·617
0·03276	0·264	0·00105	0·669
0·03085	0·275	0·00086	0·766

* Shows the break of continuity.
Inf. means the current of long duration.

Example 2 (Table II).—Middle Part of Frog's Sartorius. Bathing fluid: Ringer's solution. 3 hours 40 minutes after excision. Temperature 14·6° C.

Table II.

(*t.*)	(*e.*)	Character of twitch.
Inf.	0·159	Very slow and weak.
0·269	0·159	
0·0423	0·159	
0·03849	0·161	
0·03658	0·165	
0·03467	0·171	
0·03276	0·174	
0·03085	0·183*	
0·02894	0·188	
0·02703	0·190	
0·02512	0·205	
0·02321	0·213	
0·02130	0·244	
0·01939	0·240	
0·01844	0·247	
0·01748	0·255	
0·01653	0·267*	
0·01557	0·275	Stronger and quicker.
0·01462	0·280	
0·01366	0·289	
0·01271	0·310	
0·01175	0·323	A little weaker.
0·01080	0·350	
0·00984	0·334*	Again strong and quick.
0·00869	0·334	
0·00831	0·336	
0·00793	0·339	
0·00755	0·345	
0·00717	0·382	
0·00678	0·464	
0·00640	0·467*	A little weaker.
0·00507	0·467	
0·00487	0·663	Very strong.
0·00469	0·960	

* Shows the break of continuity.

Example 3 (Fig. 3).—Middle Part of Toad's Sartorius in Ringer's Solution 4 hours 15 minutes after excision. Temperature 13·3° C.

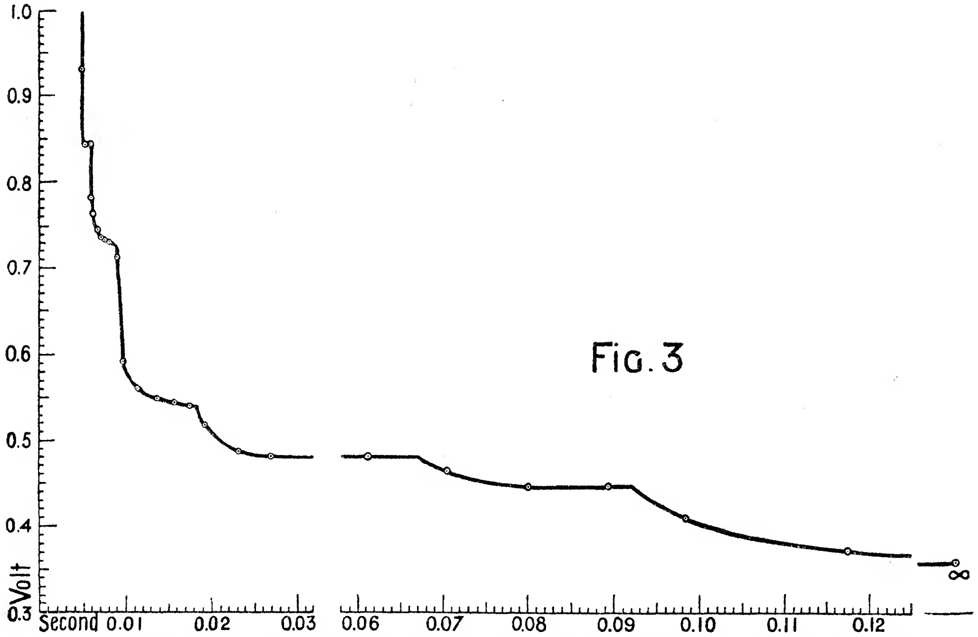

FIG. 3

FIG. 3.—Relation of current-duration to liminal voltage in the middle part of the toad's sartorius.

Example 4 (Table III).—Middle Part of M. cutaneus dorsi in Ringer's Solution, 3 hours after excision. Temperature 15° C.

Table III.

(*t*.)	(*e*.)	(*t*.)	(*e*.)
Inf.	0·086	0·01366	0·282
0·269	0·104	0·01175	0·299*
0·1175	0·104	0·01080	0·309
0·0940	0·108	0·00984	0·319
0·0846	0·123	0·00889	0·358*
0·0752	0·141*	0·00793	0·358
0·0658	0·144	0·00698	0·371
0·0564	0·155	0·00602	0·446*
0·0470	0·158*	0·00411	0·446
0·03467	0·158	0·00316	0·698
0·03085	0·166	0·00221	0·905
0·02703	0·194	0·00181	0·984
0·02321	0·204*	0·00143	1·160
0·01939	0·218	0·00105	1·489
0·01748	0·235	0·00086	1·724
0·01557	0·256	0·00067	2·088

* Shows the break of continuity.

Example 5 (Fig. 4).—Pelvic third of M. cutaneus dorsi in 0·2 per cent. Curare-Ringer's solution. The muscle was excised 1½ hours after the injection of 0·5 c.c. of 0·5 per cent. curare in the dorsal lymph-sac. The experiment began 3½ hours after excision. Temperature 12·7° C.

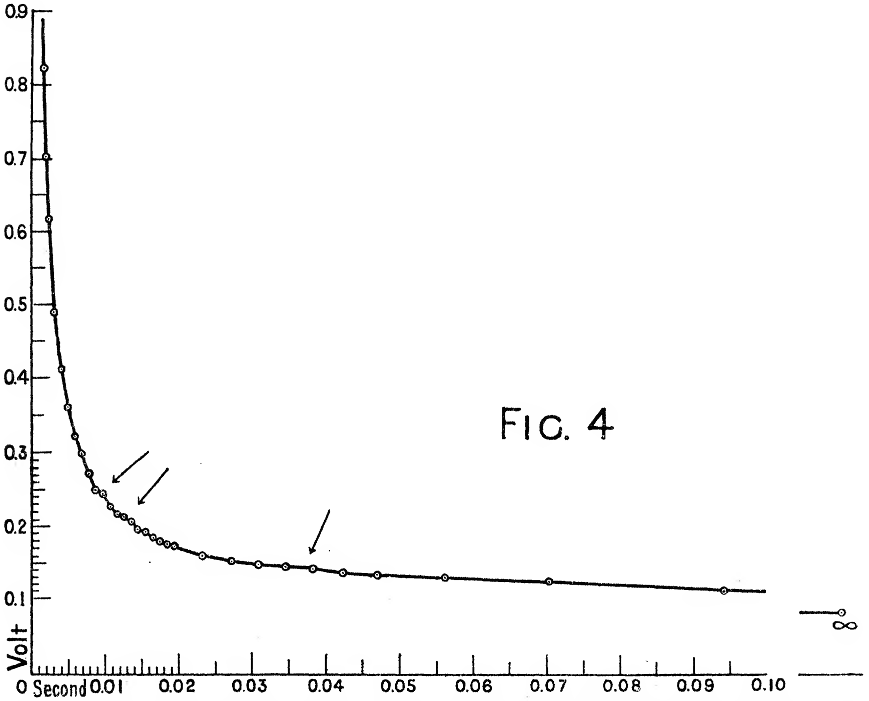

Fig. 4.—Relation of current-duration to liminal voltage in the pelvic third of curarised frog's sartorius. Arrows indicate the points at which abrupt changes in the character of contraction took place.

Example 6 (Table IV and Fig. 7B).—Pelvic end of Frog's Sartorius in Ringer's Solution, 6 hours after excision. Temperature 19·3° C.

Table IV.

(*t.*)	(*e.*)	
Inf.	0·408	
0·03849	0·514	
0·03467	0·551	
0·03123	0·576	
0·02703	0·619	
0·02321	0·669	
0·01901	0·742	
0·01748	0·778	
0·01557	0·809	
0·01366	0·851	
0·01175	0·941	
0·00793	1·939	β type.
0·00698	1·939	
0·00602	1·939	
0·00507	1·939	
0·00411	1·939	
0·00316	1·939	
0·00221	1·955	
0·00124	2·290	

PART II.—EXPERIMENTS ON A SINGLE MUSCLE-FIBRE.

Apparatus and Method.

To stimulate a single muscle-fibre, Pratt and Eisenberger (13–16) devised a non-polarisable capillary electrode and carried out successful experiments on the differentiation of the minimal contraction and the quantal phenomena in muscle. Following their descriptions, we made a capillary electrode with a pore of 10 microns in diameter, measured on the micro-photograph. The muscle-fibre of frog's sartorius being 20–40 microns in breadth, our capillary pore was capable of stimulating only one fibre.

As material for experiments, we used in the majority of cases the excised sartorius of frogs, in a few cases the muscle *in situ* and circulation, and in one case the excised cutaneus dorsi. The pelvic end of the excised sartorius, carefully prepared under Westinghaus' binocular lenses, has no fascia on its ventral surface, therefore it is possible to stimulate directly muscle-fibres in this region. A small quantity of pure carbon powder was placed on the fascia of the middle region for the convenience of the microscopic observation of responses.

The whole arrangement is shown diagrammatically in fig. 5.

The excised muscle is fixed on the paraffin bed, P, in a shallow glass vessel containing Ringer's solution, on the slide-stage of the microscope, M. C is the capillary electrode, connected with the negative pole by means of the solution, and H is its holder, which is moved up and down by a fine screw (not shown in the figure). E_1 and E_2 are electrodes, in which Zn-sulphate and Ringer's solutions are separated by the layer of 10 per cent. gelatine-Ringer gel, as in the fluid electrode described in Part I. L is the illuminating lamp.

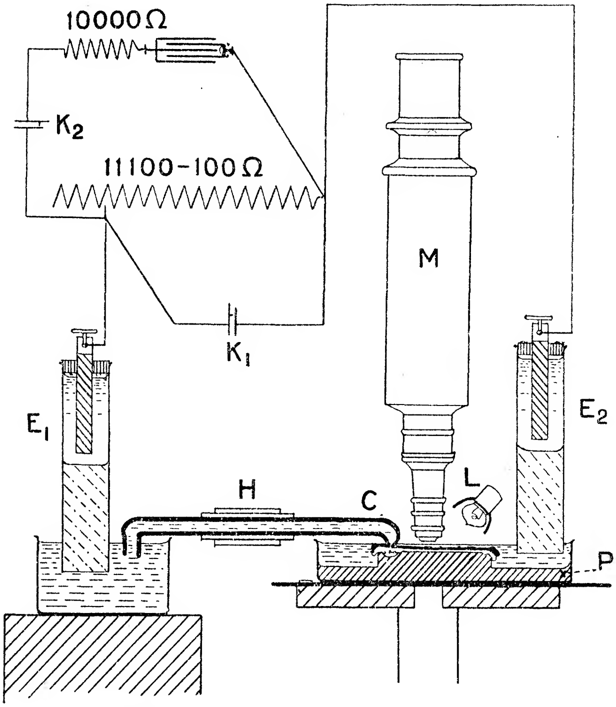

Fig. 5.—Diagram of capillary electrode.

At first, the contraction of muscle-fibres is examined under lower magnification, adjusting the capillary pore to bring the responding fibres in the middle of the microscopic field. After this preliminary manipulation the contraction of a single fibre is observed under higher magnification—about × 100.

In order to obtain good results, it is important to attach the capillary pore on the muscle as gently as possible, but perfectly, avoiding carefully blood-vessels and other obstacles. Otherwise, in the former case, the condition of muscle-fibres might be changed and the propagation of contraction hindered by the pressure of the electrode, or, in the latter case, unnecessarily large amounts of current might be employed, and it might sometimes be impossible to stimulate only one fibre.

To begin with, we examined the liminal strength for a relatively long duration of current (∞), and then stimulated regularly at an interval of

30 seconds. By the repetition of stimulation for 20–60 minutes we noticed the remarkable decrease of the liminal strength, at first rapidly and then slowly, to the final point of equilibrium. This phenomenon shows the decrease of threshold by the response, in other words, the "staircase" in excitability. At the equilibrium state of the muscle-fibre we began our experiments, keeping strictly 30 seconds' interval between two successive stimulations. After the experiments, which used to be carried out within 30 minutes, the threshold for the long-duration current was examined and compared with that in the beginning, in order to exclude such results as would be due to a change in the equilibrium state. The temperature of the bathing fluid was kept constant during the experiments.

The electrical resistance of the system being 320,000 ohms, the liminal current-strength was calculated from the same formula as given in Part I, assuming $r_3 = 320{,}000$ ohms.

Strength-duration Curve of a Muscle-fibre.

According to the "all-or-none" principle of skeletal muscle, confirmed by Lucas, Pratt, and other investigators, the absolute minimal contraction of muscle should be the contraction of a single muscle-fibre as the functional unit. Therefore, the method of experiments employed by us is undoubtedly the most rational and accurate means for the investigation of electric stimuli.

The strength-duration curves obtained from the normal muscle-fibres are in all cases quite different from the α-curve as shown below.

Example 7 (Table V and Fig. 6).—Pelvic end of Frog's Sartorius *in situ* and circulation in Ringer's solution, at 16·9° C.

Table V.

t (seconds).	i (microampères).
Inf.	1·545
0·00200	1·545
0·00181	1·548
0·00162	1·551
0·00143	1·553
0·00124	1·557
0·00105	1·565
0·00086	1·581
0·00077	1·627
0·00057	1·816
0·00038	2·442
0·00019	3·940
0·00010	7·229

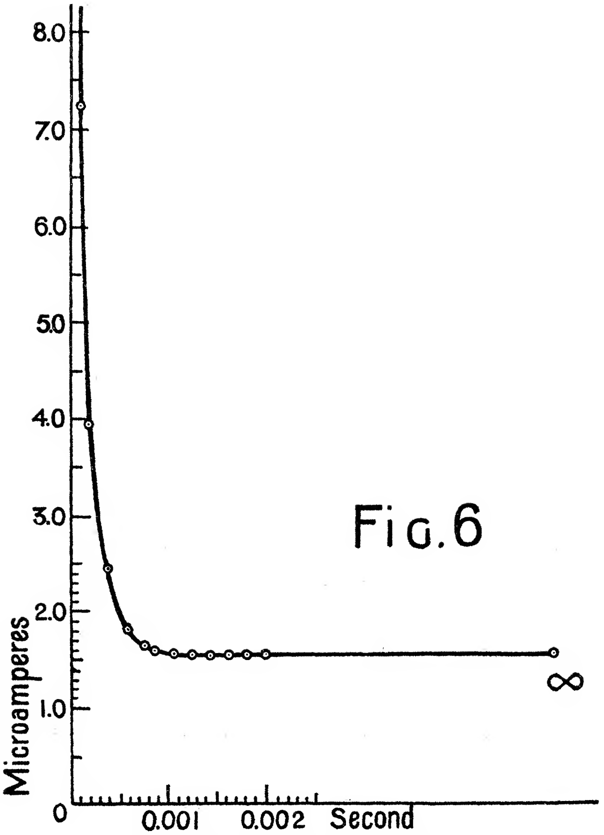

Fig. 6.—Relation of current-duration to liminal strength in the muscle fibre of frog's sartorius *in situ* and circulation. The liminal strength begins to increase at about 0·0018 seconds, and reaches twice its smallest value at about 0·00025 seconds.

Example 8 (Table VI).—Excised cutaneus dorsi in Ringer's solution, at 15·5° C.

Table VI.

t.	*i.*
Inf.	1·89
0·00257	1·89
0·00219	1·91
0·00181	1·96
0·00143	2·06
0·00105	2·35
0·00086	2·64
0·00077	2·91
0·00057	3·78
0·00038	5·43
0·00019	11·58

Example 9 (Table VII and Fig. 10c).—Excised Sartorius in Ringer's solution, at 18·1° C.

Table VII.

t.	*i.*
Inf.	1·07
0·00354	1·07
0·00257	1·08
0·00219	1·09
0·00181	1·11
0·00143	1·15
0·00105	1·22
0·00086	1·28
0·00057	1·49
0·00038	1·85
0·00019	3·80

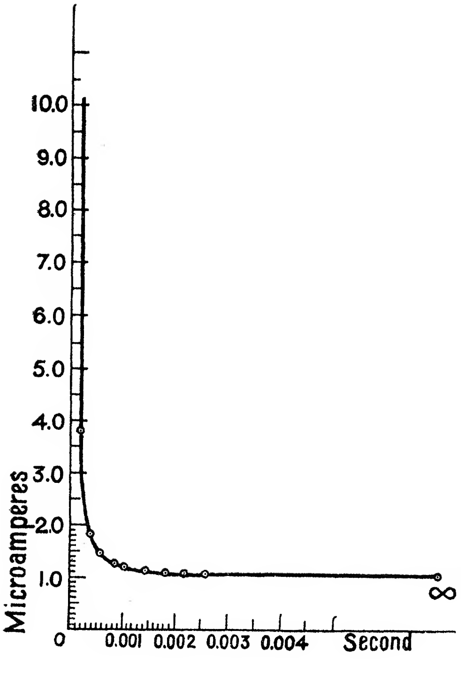

FIG.7-A

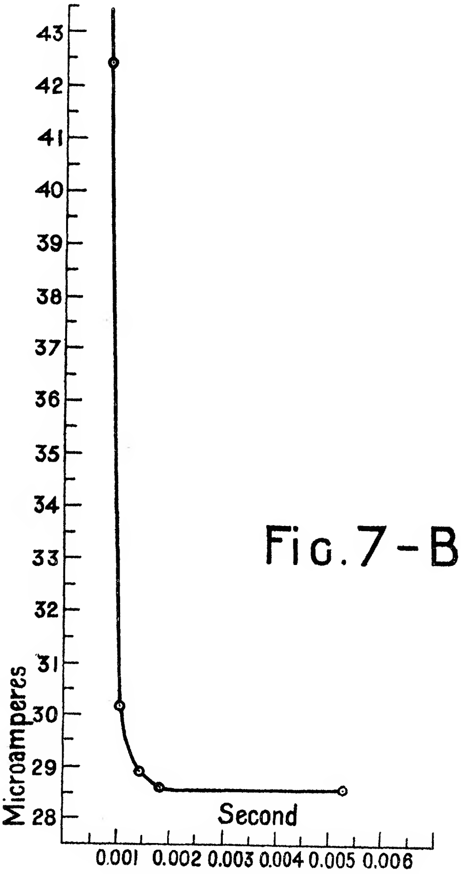

FIG.7-B

FIG. 7.—(A) Strength-duration curve of the single fibre (Example 9). (B) So-called β-curve in Example 6 (p. 59).

From these results, it is obvious that the strength-duration curves of the single fibre are quite near to the β-curve in their excitation times, that is, 0·00025—0·0003 seconds. In fig. 7 the curve of Example 9 is compared with the β-curve of Example 6.

Thus we confirmed that the characteristic strength-duration curve of muscle element is not of the so-called α-type but the β-type.

Deformation of Electric Current in Muscle.

By using Milnes' non-polarisable fluid electrode, as described in the first part of this paper, we stimulated the cutaneous end of M. cutaneus dorsi, keeping the potential difference of stimulating current always constant, and increasing or decreasing the current-duration.

After a series of preliminary stimulations to make the threshold constant, the photographic record of twitches was taken by means of the optical lever. As shown in fig. 8, the twitch increases with the increasing duration of current in definite steps. According to the "all-or-none" principle, these steps indicate the participation of new fibres or fibre-groups in twitch when the current-duration reached the value sufficient for their excitation. From other experiments we ascertained that the smaller the potential difference was, the longer the duration to produce the maximal contraction. In one case, steps were observed up to the duration of 0·1 second.

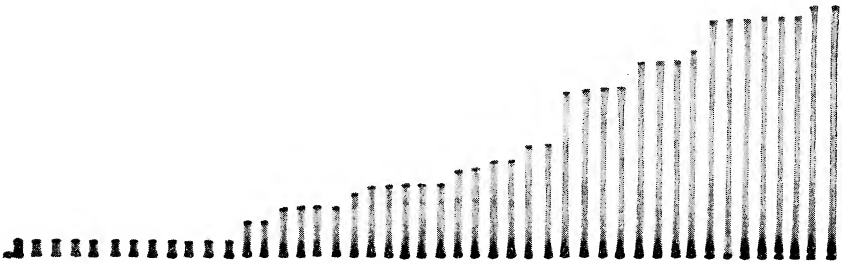

Fig. 8.—Photographic records of twitches of M. cutaneus dorsi (Magnification × 73). Current-duration increased from 0·0356 seconds to 0·0443 seconds by 0·00019 seconds ; potential difference kept constant at 0·8 volts. Interval between two successive stationary exposures is 30 seconds. Temperature 18·5° C. Records read from left to right.

To sum up these results, in the case of weak currents there seems to exist some fibre or fibre-group of very long "Hauptnutzzeit" (HNZ) (17), while by stronger currents all fibres are involved in contraction within the limit of short "HNZ." However, in our single-fibre experiments, the liminal current-strength cannot be reduced below 0·002—0·003 seconds, that is, the "HNZ" of muscle-fibres should be 0·002—0·003 seconds. From this fact, we assume that the longer "HNZ" in these experiments is nothing but the result of current deformations in muscle in the direction to increase the "HNZ."

The influence of the current deformation upon "HNZ" and strength-duration curve of a muscle-fibre is shown in the following example:—At first, we stimulated a muscle-fibre with a logarithmic current obtained by inserting a self-induction of 23 Henry and 2,700 ohms in the main circuit (fig. 9), and then we repeated the experiment without the self-induction under the same conditions.

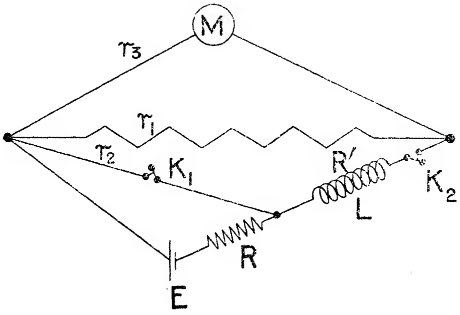

Fig. 9.

Example 10 (Table VIII and Fig. 10).—Excised Sartorius in Ringer's solution.

Table VIII.

Experiment 1.—4½ hours after excision, at 17·9° C.			Experiment 2.—5 hours 20 minutes after excision, at 18·1° C.
t.	i_a.	i_b.	
Inf.	1·08	1·07	(See Table VII.)
0·00831	1·08	1·07	
0·00731	1·09	1·07	
0·00640	1·10	1·07	
0·00545	1·13	1·08	
0·00449	1·18	1·09	
0·00354	1·29	1·12	
0·00257	1·52	1·17	
0·00219	1·67	1·20	
0·00181	1·92	1·26	
0·00143	2·36	1·36	
0·00105	3·22	1·53	
0·00086	4·12	1·74	
0·00057	6·65	2·20	
0·00038	11·18	3·14	

The liminal current-strength calculated from the following formula, taking into account the deformation of current due to the self-induction, is shown as Curve *b*, fig. 10.

$$i_b = i_a\{1-e^{-(r_1+\mathrm{R}+\mathrm{R}')\,t/\mathrm{L}}\}$$

where L and R′ are the inductance and resistance of the self-induction. If we neglect the current deformation, the calculated strength i_a is plotted as *a* The result, without self-induction, is *c*. Not only is the difference in the excitation time and "HNZ" between *b* and *c* remarkable, but also it is an important fact that we obtain quite different curves from the same fibre by merely neglecting the deformation of currents from the calculation, as *a* and *b*.

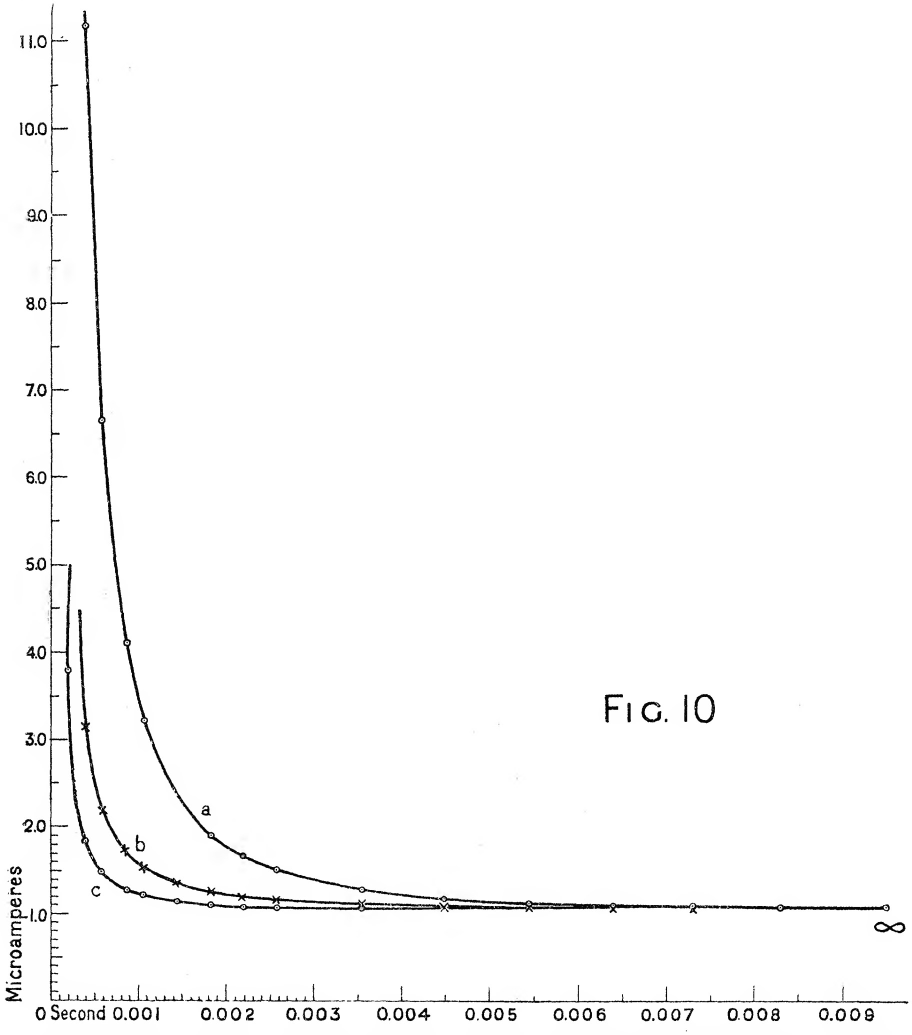

FIG. 10.—Influence of current-deformation on the strength-duration-curve. (*a*) The liminal strength begins to increase at about 0·0073 seconds, and is doubled at about 0·0016 seconds. (*b*) Corresponding values are 0·0054 and 0·0006 seconds. (*c*) Corresponding values are 0·0025 and 0·0003 seconds.

Therefore, it is possible that muscle-fibres of the same character might show several different curves in accordance with the extent of the deformation of stimulating currents.

Discussion and Conclusion.

As the strength-duration curve obtained by the experiment on a muscle as a whole may be considered as the composite curve of those of muscle-fibres, therefore, it is conceivably possible to obtain a complex curve, according to the various extent of the current deformation at every part of the muscle. And the more accurate methods of investigation are employed, the more breaks in the continuity of curves are to be found. In one case, we happened to stimulate two adjoining fibres at a time, and observed a break of continuity in the curve.

As for the elimination of the β- and γ-curves by curare, the following experiments may offer some explanation :—

Example 11.

A (Table IX and Fig. 11, *a*).—Excised Sartorius in 0·05 per cent. Curare-Ringer's solution, at 19·2° C.

Table IX.

t.	*i.*
Inf.	0·75
0·00640	0·75
0·00449	0·77
0·00257	0·87
0·00162	0·99
0·00105	1·17
0·00086	1·30
0·00057	1·71
0·00038	2·37
0·00019	5·50

B (Table X and Fig. 11, *b*).—Excised Sartorius in 0·001 per cent. Curare-Ringer's solution, at 18·5° C.

Table X.

t.	*i.*
Inf.	0·67
0·00219	0·67
0·00181	0·68
0·00143	0·70
0·00105	0·76
0·00086	0·82
0·00057	1·01
0·00038	1·36
0·00019	3·01

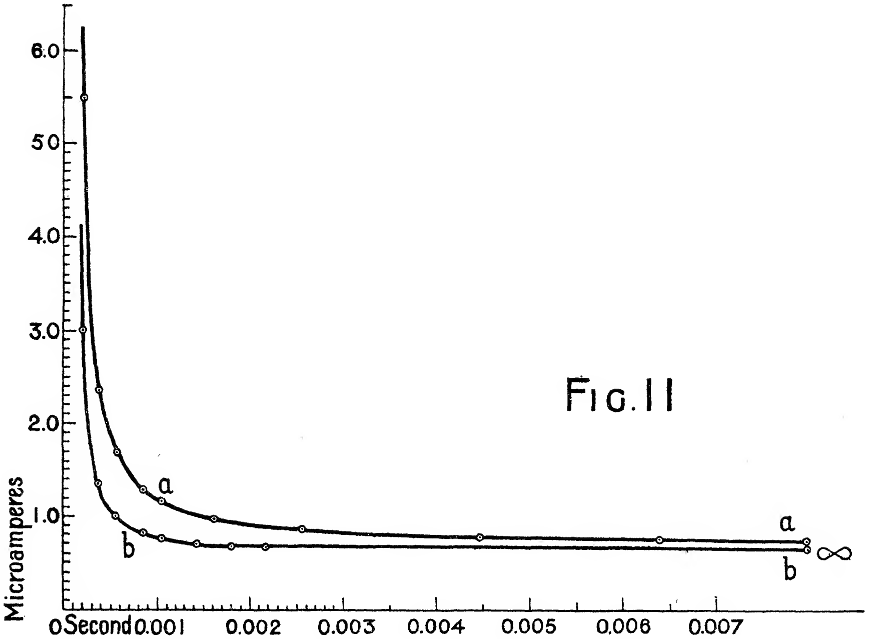

Fig. 11.—Influence of curare on the strength-duration curve of the muscle fibre. (*a*) 0·05 per cent. curare. The liminal strength begins to increase at about 0·0064 seconds, and is doubled at about 0·0007 seconds. (*b*) 0·001 per cent. curare. The corresponding values are 0·0018 and 0·0004 seconds.

From these results it is obvious that the strength-duration curve becomes less steep with strong doses of curare, and this is the reason why the β-curve is abolished.

In short, the curve of β type can be obtained when the current stimulates all fibres in the same manner as in the case of stimulating a normal fibre by the capillary electrode. This is the condition which may be fulfilled only by fairly strong currents, as shown by the experimental results.

Thus, as for the existence of the β-curve, we are inclined to believe that it should be attributed to the muscle elements under a certain condition of the stimulating current, but not to the specific intermediary substance.

The suggestive factors for the deformation of electric current in the excitable tissues are as follows:—

(1) Assuming that an excitable element contains membranes impermeable to the dissolved ions, we might expect a relatively large capacity, as a consequence of which the stimulating current attains its full strength after a certain time (Ladungszeit). (2) The high electrical resistance of the intercellular tissue fluid, through which the stimulating current enters into deep fibres, might have some influence in this connection. (3) In consequence of

the impermeability of the membrane, the polarisation might occur with the flow of the stimulating current and cause the decrement of the current-strength, which is also variable with the current-strength and resistance. (4) If the alterations in the permeability of membrane during the process of excitation, and (5) the consumption of some ions for the further chemical process are possibly taken into consideration, the deformation of the electric current as the stimulus might be a very complicated phenomenon.

SUMMARY.

(1) In the first part of our experiments, we followed Lucas' method, with our own new devices, that is, first in regard to the contact-breaker, which is capable of producing a constant current of short duration in the range of 0·0001–0·27 seconds, and secondly, in respect to the distribution of resistances in the stimulating system.

Nearly all our experiments caused similar results, *i.e.*, when M. sartorius or cutaneus dorsi of the frog was stimulated, not only Lucas' so-called β- and γ-curves, but also many branches of curves belonging to the α-type (in the case of the relatively long duration of current) made their appearance. Even when the β- and γ-curves were abolished by the action of strong doses of curare the discontinuity of curves remained unchanged. According to the argument of Lucas, such discontinuity should prove the existence of muscle-fibres of various excitability. But this conclusion could be deduced only from such an assumption as that the constant current would enter into each excitable element equally without altering its time-relation. If the stimulating current which flows through an excitable tissue enters into each element under various time-relations owing to the arrangement employed, the break in the curve might be produced, even when the tissue consists of similar excitable elements.

(2) In the second part of the experiments we studied the excitatory effect of the electric current on a single muscle-fibre which represents a functional element of the muscle tissue. In this case, the strength-duration curve is quite analogous to so-called β-curve, while the α-curve cannot be found anywhere. That the β- and γ-curves seem to be abolished by the action of curare is only an appearance which comes forth as a consequence of the alterations in elemental curves thereby. The difference of the results between a single fibre and a muscle as a whole might be caused by the deformation of the stimulating current as it enters into the excitable tissue.

(3) Under the constant value of the potential difference, the regular increase of the duration of stimulating current causes the increase of the contraction of muscle with distinct steps. The "all-or-none" principle of

skeletal muscle-fibres indicates to us that each step in the increase of contraction means that the contraction of some new muscle-fibres has been added to the former when current-duration has reached the necessary value for the excitation of these fibres. Many photographic records of this phenomenon were taken by the use of Mines' non-polarisable fluid electrode, in which M. cutaneus dorsi was suspended in connection with the optical lever. Occasionally it happened that the further increase of contraction was conspicuously observed even at the current-duration of 0·05 or 0·1 second, while in the results of the experiments on a single fibre, the increase in current-duration of more than 0·002—0·003 seconds does not effect the decrease of the liminal current-strength. Therefore the contraction of muscle in the fluid electrode should not increase at a current-duration of more than 0·003 second if the electric current entered into each fibre with equal time-relation, as in the case of a single fibre stimulated by the capillary electrode. But the fact stands obviously against this supposition. Thus the assumption might be made that the electric current enters into deep fibres of the muscle tissue with so much delay, as in the case of self-induction, that these fibres will not be excited unless the duration of current is very much prolonged.

(4) The possible factors for the deformation of stimulating current as it flows through the excitable tissue are suggested in the conclusion.

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